Hints of a Charge Asymmetry in the Electron and Positron Cosmic-Ray Excesses

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Abstract

By combining the recent data from AMS-02 with those from Fermi-LAT, we show the emergence of a charge asymmetry in the electron and positron cosmic-ray excesses, slightly favoring the electron component. Astrophysical and dark matter inspired models introduced to explain the observed excesses can be classified according to their prediction for the charge asymmetry and its energy dependence. Future data confirming the presence of a charge asymmetry, would imply that an asymmetric production mechanism is at play.

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I. INTRODUCTION

Electron and positron fluxes in Cosmic Rays (CRs) have been measured by many experiments. For energies above about 10 GeV the positron fraction displays a rising behavior. The total flux also displays some features around 100 GeV. There is a common agreement on the fact that these data cannot be interpreted solely in terms of known astrophysical sources. An unknown source of electrons and positrons CRs has to be introduced in order to account for the excesses seen on the top of the background fluxes, associated to known astrophysical sources. We refer to [1, 2] for recent reviews.

In [3] we suggested a strategy to investigate the possible charge asymmetry in the electron and positron CRs excesses; as a result, we showed that, at that time, even large deviations from charge symmetry were experimentally viable. This kind of analysis deserves now to be updated in the light of the recent data collected by AMS-02 [4] and by Fermi-LAT [5, 6]. This is precisely the goal of this paper. Future experimental observations could even better constrain the amount of charge asymmetry.

The amount of the charge asymmetry of the CR lepton excesses is crucial to understand the physical properties of the unknown source. Among the many candidates suggested, there are for instance: astrophysical sources, like supernovae or pulsars (see *e.g.* [1, 2, 7–10]), which are expected to be charge symmetric; dark matter (DM) annihilations and/or decays. Contrary to the case of annihilating DM, decaying DM can lead to a charge asymmetry provided that both charge conjugation and lepton flavor are violated [11].

The paper is organized as follows. In sec. II we review the experimental data to be used in the analysis. Section III introduces the notations and a useful relation [3]. After having discussed background models in sec. IV, in sec. V we investigate the experimental status of the charge asymmetry. Here we find a hint of an asymmetric excess, favouring the electron component over the positron one. We conclude in sec. VI, where we offer the physical applications and interpretations of our results.

II. DATA ON ELECTRON AND POSITRON CRS FLUXES

We now briefly summarize the experimental data on electron and positron CRs fluxes, $\phi_{e^-}(E)$ and $\phi_{e^+}(E)$, where E is the energy of the detected $e^\pm$.

In 2009, the PAMELA experiment [12] measured the positron fraction, $\phi_{e^+}(E)/(\phi_{e^-}(E) + \phi_{e^+}(E))$, between 1 and 100 GeV, finding that it unexpectedly increases above 10 GeV. This rising behavior is difficult to explain via secondary production of positrons in interactions of high energy hadronic CRs. Therefore it has been interpreted as a positron anomalous excess in the CR energy spectrum above 10 GeV. This would imply the existence of an unknown source of CR positrons - see for instance the nice dis-

cussion in [8]. On the other hand PAMELA did not observe any excess in the anti-protons spectrum [13].

Already in 2008 ATIC [14] and PPB-BETS [15] reported an unexpected structure in $\phi_{e^-}(E)+\phi_{e^+}(E)$, in the energy range between 100 GeV and 1 TeV. The picture was soon corroborated via the higher-statistics measurements by Fermi-LAT [16] and H.E.S.S. [17], that suggested a possible small additional unknown component in the total flux, on the top of the standard astrophysical model predictions. The latter generically assume a single-power-law injection spectrum of $e^\pm$. Fermi-LAT [5] determined that the total $e^\pm$ spectrum in the energy range 7 GeV$< E <$ 1 TeV is indeed compatible with a power-law of index -3.08 ± 0.05, but it also displays significant evidence of a spectral hardening above 100 GeV.

In 2011, new experimental informations were added. PAMELA measured the electron spectrum between 1 and 625 GeV [18]. Fermi-LAT [6] measured the separate cosmic-ray electron and positron spectra, thought with a worse sensitivity than the total spectrum.

Very recently, AMS-02 [4] measured the CR positron fraction with unprecedented precision and up to energies of about 350 GeV. This experimental information, together with the precise determination of the total flux by Fermi-LAT [5], at present, calls for a new study of the charge asymmetry in the electron and positron excesses. This is what we will perform next following the strategy proposed in [3].

III. NOTATION AND SUM RULE

The observed flux of electrons and positrons can be written as the sum of two contributions: a background component $\phi^B_{e^\pm}(E)$, describing all known astrophysical sources; an unknown component $\phi^U_{e^\pm}(E)$ (of whatever origin), which is needed to explain the features in the spectra observed by experiments. Explicitly,

$$\phi_{e^+}(E) = \phi^U_{e^+}(E) + \phi^B_{e^+}(E)\,, \quad \phi_{e^-}(E) = \phi^U_{e^-}(E) + \phi^B_{e^-}(E)\,. \tag{1}$$

AMS-02 and Fermi-LAT measure respectively the positron fraction and the total electron and positron fluxes as a function of the energy E:

$$F_+(E) = \frac{\phi_{e^+}(E)}{\phi_{e^+}(E)+\phi_{e^-}(E)}\,, \qquad T(E) = \phi_{e^+}(E)+\phi_{e^-}(E)\,. \tag{2}$$

The left-hand side of the equations above refer to the experimental measures. Given such data, our aim is to investigate the unknown contribution leading to the lepton excesses:

$$\begin{aligned} \phi^U_{e^+}(E) &= F_+(E)\; T(E) - \phi^B_{e^+}(E)\,, \\ \phi^U_{e^-}(E) &= T(E)\;\left(1 - F_+(E)\right) - \phi^B_{e^-}(E)\,. \end{aligned} \tag{3}$$

Clearly, this can be done only by *assuming* an astrophysical background model, as discussed below.

Here we are interested in particular in a fundamental property of the unknown contribution: its charge asymmetry [3]. The ratio of the unknown electron and positron fluxes is a direct measure of such charge asymmetry:

$$r_U(E) \equiv \frac{\phi^U_{e^-}(E)}{\phi^U_{e^+}(E)} = \frac{T(E)\ (1 - F_+(E)) - \phi^B_{e^-}(E)}{F_+(E)\ T(E) - \phi^B_{e^+}(E)} \quad . \tag{4}$$

Note that this equation can be rewritten as a *sum rule* [3],

$$\frac{T(E)}{\phi^B_{e^-}(E)} \ \frac{1 - (1 + r_U(E))F_+(E)}{1 - r_U(E)\frac{\phi^B_{e^+}(E)}{\phi^B_{e^-}(E)}} = 1 \ , \tag{5}$$

that links together the experimental results, the model of the backgrounds and the dependence on the energy of the charge asymmetry of the unknown excesses. We use the $E \gtrsim 25$ GeV data bins, since the lower energy bins are affected by the solar modulation.

IV. ASTROPHYSICAL BACKGROUND MODELS

Primary electrons can come from galactic CRs while interactions of CRs with the interstellar medium sources secondary electrons, positrons and antiprotons. The propagation of the signal and background fluxes from their production region to the detector is affected mainly by diffusion and energy losses. We evaluate the background fluxes at Earth using the studies [7, 19–21]. These fluxes can be conveniently described by a power low, with a global normalization and a spectral index. We discuss below the impact of the spectral index uncertainties.

We model the background spectrum using

$$\phi^B_{e^\pm}(E) = N^B_{e^\pm}\ B_{e^\pm}(E) \quad , \tag{6}$$

where $N^B_{e^\pm}$ are normalization coefficients and $B_{e^\pm}(E)$ are provided using specific astrophysical models. In this paper we adopt various models, in order to study how much the results are affected by the background model choice. In particular, measuring E in GeV and the B's in units of GeV^{-1}cm^{-2}sec^{-1}sr^{-1}, we consider the following models.

- Moskalenko and Strong (MS) [22], a popular model (used also in [23, 24]) for which

$$\begin{aligned} B_{e^+}(E) &= \frac{4.5E^{0.7}}{1 + 650E^{2.3} + 1500E^{4.2}} \ , \\ B_{e^-}(E) &= \frac{0.16E^{-1.1}}{1 + 11E^{0.9} + 3.2E^{2.15}} + \frac{0.70E^{0.7}}{1 + 110E^{1.5} + 600E^{2.9} + 580E^{4.2}} \ . \end{aligned} \tag{7}$$

- Spectral Index (SI) model, a generic model that we parametrize as:

$$
\begin{aligned}
B_{e^+}(E) &= 1.40 \times 10^{-4} \left(\frac{E}{E_0}\right)^{-\gamma_{e^+}} , \\
B_{e^-}(E) &= 5.43 \times 10^{-3} \left(\frac{E}{E_0}\right)^{-\gamma_{e^-}} .
\end{aligned}
\tag{8}
$$

  where $E_0 = 33.35$ GeV. The normalization coefficients of the SI model have been chosen so that the $B_{e^\pm}$ functions equate those of the MS model at $E = E_0$. Note also that the SI model with $\gamma_{e^-} = 3.21$ and $\gamma_{e^+} = 3.41$ actually corresponds to the Fermi Collaboration (FC) model zero [25, 26]. The SI model with $\gamma_{e^+} = 3.5$ approximates very well the positron background of the MS model. The electron background of the MS model has spectral index 3.25 for energies above 100 GeV.

The background models are illustrated in fig. 1, assuming for definiteness $N^B_{e^\pm} = 0.73$. The natural range of the electron spectral index of the SI model is $\gamma_{e^-} = [3.18, 3.26]$, while the natural range of the positron spectral index is $\gamma_{e^+} = [3.4, 3.5]$ (see for instance [7, 19, 20]). The FC model can thus be seen as an SI model with intermediate values of the spectral indexes. For comparison, the plot also shows the Fermi-LAT data points for the total [5] and separate electron and positron fluxes [6]. To make a comparison with other recent studies, we note that refs. [23, 24] focus on the MS model, allowing for variations of its spectral index of about 0.05; this corresponds to our SI model with $\gamma_{e^-} = [3.19, 3.29]$ and $\gamma_{e^+} = [3.45, 3.55]$.

The energy dependence of the background fluxes is encoded in the $B_{e^\pm}(E)$ functions but, as can be seen from eq. (6), there is also the problem of fixing the normalization coefficients $N^B_{e^\pm}$. As we are going to discuss, in order to characterize a certain background model, it is not necessary to make two independent assumptions on $N^B_{e^-}$ and $N^B_{e^+}$, but just one assumption on their ratio:

$$
r_B = \frac{N^B_{e^-}}{N^B_{e^+}} . \tag{9}
$$

If we focus on a certain energy bin $\bar{E}$ where both the positron fraction F_+ and the total flux T have been measured, eq. (5) can indeed be used to derive a range for $N^B_{e^-}$:

$$
N^B_{e^-}(r_U(\bar{E}), r_B) = \frac{T(\bar{E})}{B_{e^-}(\bar{E})} \, \frac{1 - (1 + r_U(\bar{E}))F_+(\bar{E})}{1 - \frac{r_U(\bar{E})}{r_B} \frac{B_{e^+}(\bar{E})}{B_{e^-}(\bar{E})}} . \tag{10}
$$

For a certain background model (characterized by the $B_{e^\pm}(E)$ functions) and using the experimental data on $T(\bar{E})$ and $F_+(\bar{E})$, the allowed range for $N^B_{e^-}$ can be calculated by making assumptions on the values of $r_U(\bar{E})$ and r_B. For the sake of our analysis, we consider it safe to let r_B vary in the range $[0.5, 2]$ (as done also in [23, 24]).

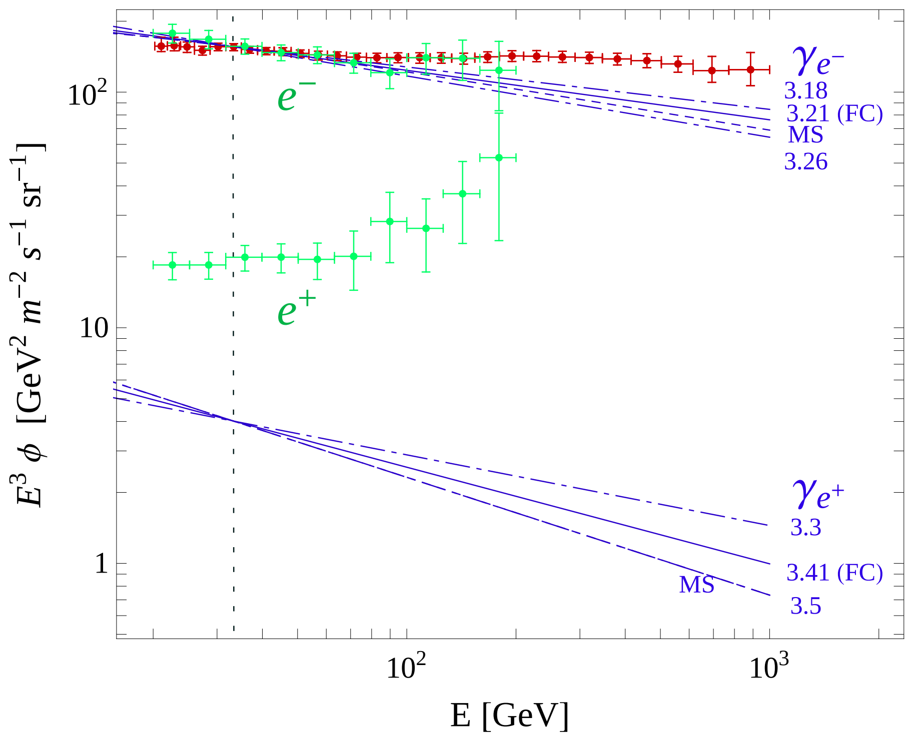

FIG. 1: Models for background fluxes: MS (dashed), SI for extreme (dot-dashed) and intermediate (solid) values of the spectral indexes. The latter corresponds to the FC model. The fluxes have been normalized by choosing $N^B_{e^\pm} = 0.73$. The Fermi-LAT experimental data on the the total flux [5] (red) and separate electrons and positrons fluxes [6] (green) are also shown for comparison.

We consider in particular $\bar{E} = 33.35$ GeV (for which $B_{e^-}(\bar{E})/B_{e^+}(\bar{E}) = 38.82$) and display the results for $N^B_{e^-}$ in fig. 2, showing the dependence on r_B for fixed values of $r_U(\bar{E})$ in the left panel, viceversa in the right panel. The thickness of the curves is obtained by considering the variation of $N^B_{e^-}$ associated to the 1σ ranges of $T(\bar{E})$ and $F_+(\bar{E})$. The variation due to $T(\bar{E})$ turns out to be the dominant one.

V. CONSTRAINING THE CHARGE ASYMMETRY

Having derived a range for the normalization of the electron background $N^B_{e^-}$ as a function of $r_U(\bar{E})$ and r_B (so that both T and F_+ values are reproduced at a certain energy $\bar{E}$), we can use it to extrapolate the positron fraction at any energy value. We can

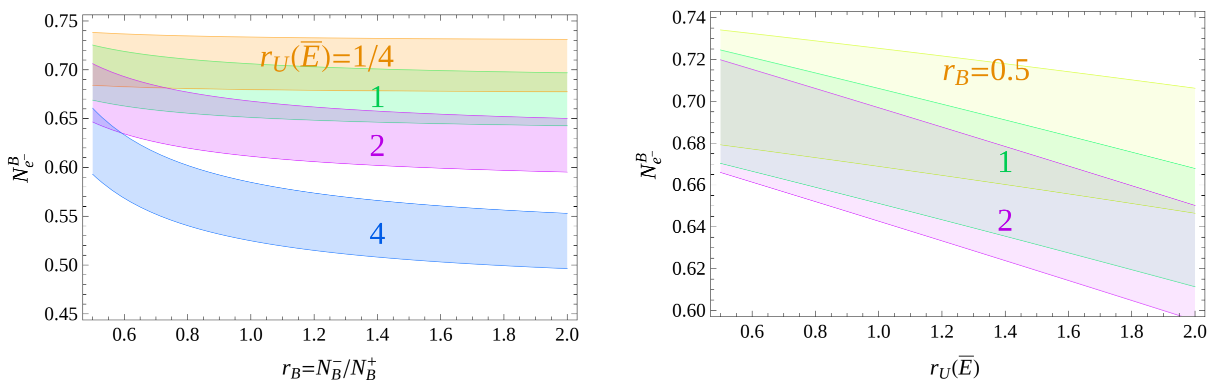

FIG. 2: Values of $N^B_{e^-}$ according to eq. (10) assuming $\bar{E} = 33.35$ GeV. Left: as a function of r_B for different values of $r_U(\bar{E})$. Right: as a function of $r_U(\bar{E})$ for different values of r_B. The thickness of the bands is obtained by considering the 1σ ranges of $F_+(\bar{E})$ from AMS-02 [4] and $T(\bar{E})$ from Fermi-LAT [5].

in fact rewrite eq. (5) as follows:

$$F_+(E) = \frac{1}{1+r_U(E)}\left[1 - N^B_{e^-}(r_U(\bar{E}), r_B)\,\frac{B_{e^-}(E)}{T(E)}\left(1 - \frac{r_U(E)}{r_B}\frac{B_{e^+}(E)}{B_{e^-}(E)}\right)\right]. \tag{11}$$

Suppose now that we specify a background model (namely $B_{e^+}(E), B_{e^-}(E), r_B$) and that we make an assumption on $r_U(E)$: it is then possible to check the consistency between the extrapolation for different energy values based on eq. (11) and the experimental data. Clearly, if we use the range of values for $N^B_{e^-}(r_U(\bar{E}), r_B)$ discussed previously, we are guaranteed that both the total flux and the positron fraction reproduce the experimental data in the $\bar{E}$ energy bin.

A. Energy independent $r_U(E)$

In order to test whether current CRs data could support charge asymmetric lepton excesses, as done in [3], the first step is to consider the oversimplifying assumption that r_U is nearly constant in the energy region of interest.

The extrapolation of the positron fraction, assuming that r_U remains constant over the entire energy range (from about 30 GeV up to about 700 GeV), is shown in fig. 3 for the FC (shaded) and MS (dashed) background models and by taking $r_B = 1$. We focus in particular on the cases $r_U = 0, 1/2, 1, 2, 4$ (from top to bottom). The thickness of the curves correspond to the 1σ ranges of AMS-02 [4] and Fermi-LAT [5]. One should not be worried by the wiggles between in the $30-50$ GeV, as they are simply due to the features

of the data points in that range. The picture shows that the current data are consistent with $r_U = 1$ for energies up to 100 GeV, but favor a deviation from charge symmetry at energies above 100 GeV, where the preferred charge asymmetry value is $r_U \sim 2$: the latter value means that the electron excess of unknown origin should be about twice the positron one.

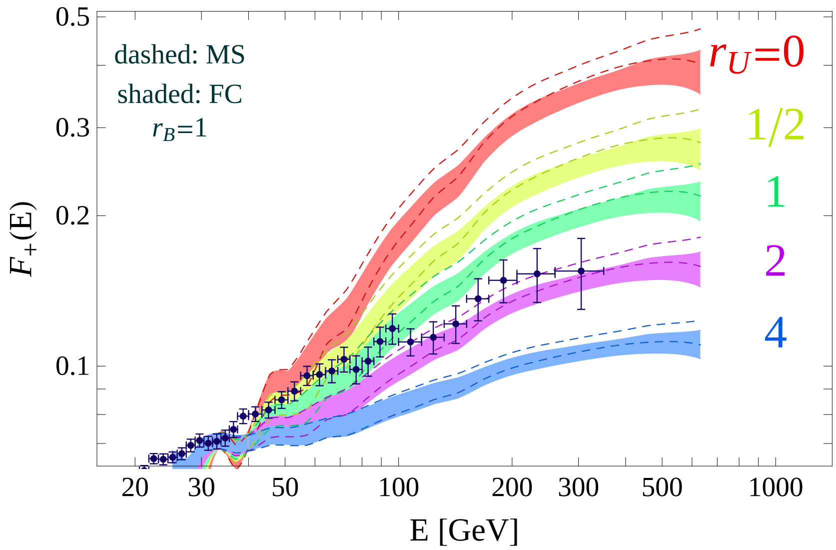

FIG. 3: Positron fraction $F_+(E)$ for different values of r_U, according to eq. (11). The shaded (dashed) curves refer to the FC (MS) background model with $r_B = 1$. The AMS-02 data [4] with 1σ error bars (statistical and systematic combined in quadrature) are shown for comparison.

These interesting results makes it mandatory a deeper study of their dependence on the model background: this can be done by considering the impact of varying r_B and the spectral indexes $\gamma_{e^\pm}$.

Focusing on the FC background model for definiteness, the top panel of fig. 4 displays the dependence on r_B. Lowering r_B goes in the direction of reducing the positron fraction, alleviating the tension between the AMS-02 data [4] and the charge symmetric case above 100 GeV. However, the global shift turns out not to be strong enough to account for $r_U = 1$.

As a second study of the robustness of the deviation from charge symmetry above 100 GeV, we consider a generic SI model with $r_B = 1$ and analyze its dependence on γ_{e^-} and γ_{e^+}: this is done respectively in the middle and bottom panels of fig. 4. We can see that while γ_{e^-} has a significative impact on the slope of the positron fraction, γ_{e^+} does not affect it much. The tension with charge symmetry above 100 GeV is nearly removed for values of γ_{e^-} smaller than 3.18.

As a further test of our results, we perform a chi-squared test using the following test

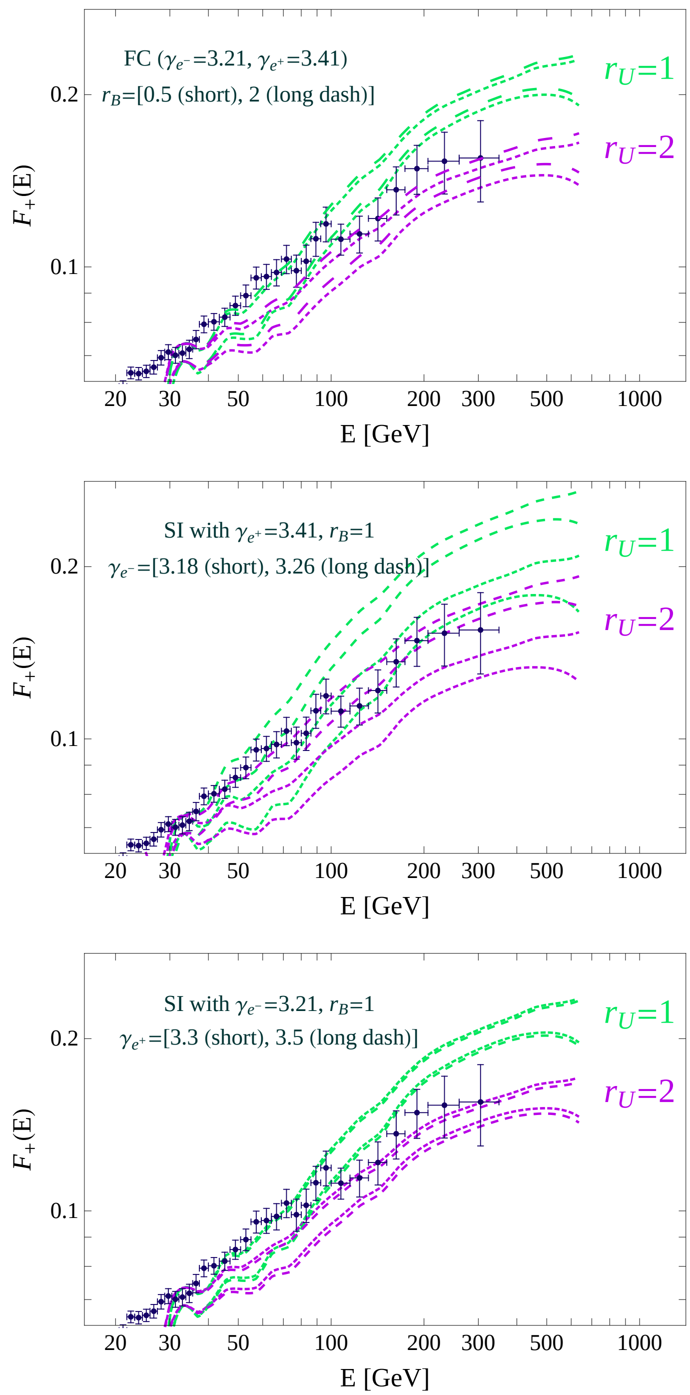

FIG. 4: Positron fraction $F_+(E)$ for different values of r_U. The AMS-02 data [4] with 1σ error bars are shown for comparison. Top: dependence on r_B for FC model. Medium: dependence on γ_{e^-} for SI model with $\gamma_{e^+} = 3.41$ and $r_B = 1$. Bottom: dependence on γ_{e^+} for SI model with $\gamma_{e^-} = 3.21$ and $r_B = 1$.

function. For the background we assume the following SI form,

$$\phi^B_{e^\pm}(E) = N^B_{e^\pm}\, E^{-\gamma_{e^\pm}} \,, \tag{12}$$

while for the unknown source we consider

$$\phi^U_{e^\pm}(E) = N^U_{e^\pm}\, E^{-\gamma_U}\, e^{-E/E_U} \ . \tag{13}$$

The associated charge asymmetry is constant and parametrized by $r_U = N^U_{e^-}/N^U_{e^+}$. We fit the AMS-02 [4] and Fermi-LAT data [5] to the following seven free parameters for a given r_U:

$$\frac{N^B_{e^-}}{N^B_{e+}},\ \gamma_{e^-} - \gamma_{e^+},\ \frac{N^U_{e^-}}{N^B_{e^-}},\ \gamma_U - \gamma_{e^-},\ E_U,\ N^B_{e^-},\ \gamma_{e^-}\ , \quad \text{free parameters}\,. \tag{14}$$

A reasonable agreement with data, according to the chi-squared distribution, can be obtained for any value of r_U between 1 and 2. We find that for lower values of r_U, γ_{e^-} turns out to be small, around $3.14 - 3.16$ at 90% C.L. for $r_U = 1$. For $r_U = 2$ instead the γ_{e^-} range is $3.205 - 3.225$. These results are in agreement with our previous comments that a value of γ_{e^-} closer to the astrophysically expected range $3.18 - 3.26$, is obtained for $r_U \sim 2$.

B. Deriving $r_U(E)$ from data

For various background models, we now study directly the charge asymmetry of the unknown excesses, $r_U(E) = \phi^U_-(E)/\phi^U_+(E)$, by considering its expression given in eq. (4), which we report here:

$$r_U(E) = \frac{T(E)\ (1 - F_+(E)) - N^B_{e^-}(r_U(\bar{E}), r_B)\, B_{e^-}(E)}{F_+(E)\ T(E) - \frac{N^B_{e^-}(r_U(\bar{E}), r_B)}{r_B}\, B_{e^+}(E)} \ . \tag{15}$$

Such study can be done by assuming a background model (namely $B_{e^+}(E), B_{e^-}(E), r_B$) and making an assumption on $r_U(\bar{E})$.

In the top panel of fig. 5 we display the $r_U(E)$ range for the MS (dashed), FC (shaded) and SI (dot-dashed) models, assuming $r_B = 1$ and $r_U(\bar{E}) = 1$. For the SI model we choose $\gamma_{e^-} = 3.18$ and $\gamma_{e^+} = 3.41$. The thickness of the curves corresponds to the 1σ ranges of AMS-02 [4] and Fermi-LAT [5]. Despite the oscillations below 50 GeV (which are simply due to the pattern of the experimental data points), one can see that $r_U(E)$ displays an increasing behavior with energy. A transition occurs above 100 GeV, where $r_U(E)$ becomes bigger than unity, spanning the range between 1 and 2, for the MS and FC models. The SI model with a low value of the electron spectral index, $\gamma_{e^-} = 3.18$, is instead compatible with charge symmetry.

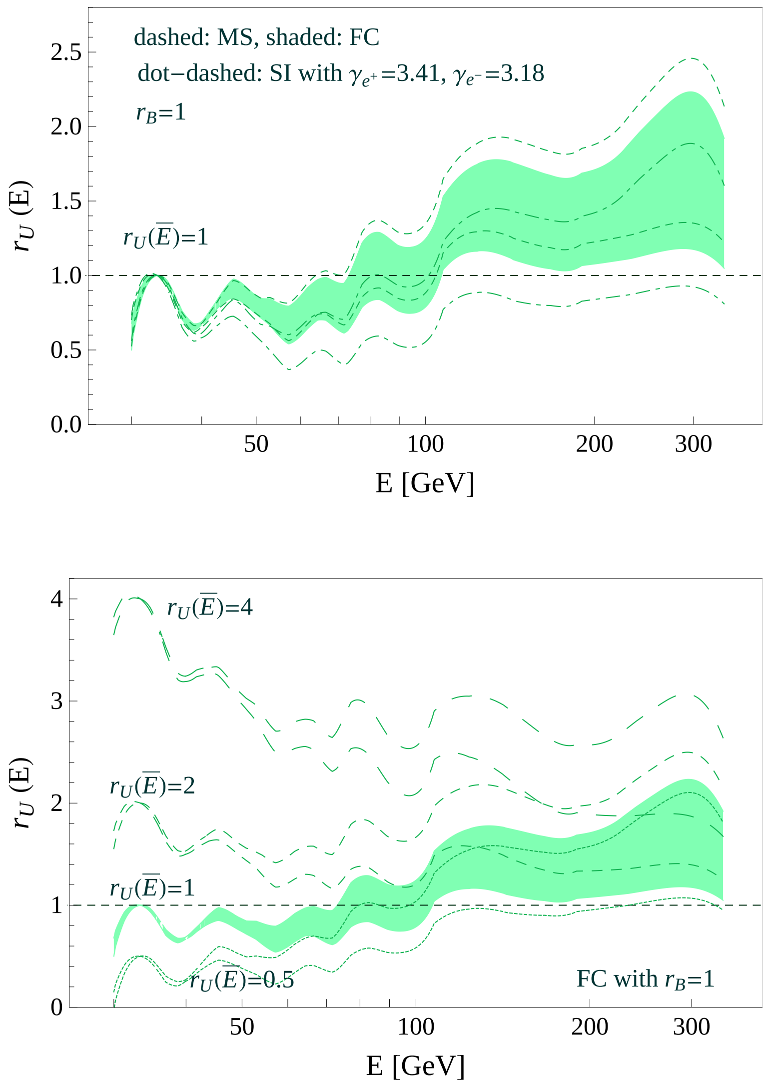

FIG. 5: Ratio $r_U(E)$ according to eq. (15). Top: for the MS (dashed), FC (shaded) and SI (dot-dashed) models with $r_B = 1$ and $r_U(\bar{E}) = 1$. Bottom: for the FC model with $r_B = 1$ and various values of $r_U(\bar{E})$. The thickness of the curves corresponds to the 1σ ranges of AMS-02 [4] and Fermi-LAT [5].

Since we are particularly interested in deviations from charge symmetry, it is important to study the dependence of $r_U(E)$ on the value chosen for $r_U(\bar{E})$. This is done in the bottom panel of fig. 5, focusing on the FC model with $r_B = 1$. One can see that for whole interval $r_U(\bar{E}) = [0.5, 4]$, $r_U(E)$ is bigger the unity above 100 GeV. In addition, $r_U(\bar{E}) \sim 2$ is the sole case that allows $r_U(E)$ to be nearly energy independent. For $r_U(\bar{E}) > 2$ ($r_U(\bar{E}) < 2$), $r_U(E)$ is a decreasing (increasing) function of the energy. We also considered the dependence of the $r_U(E)$ on the value chosen for r_B, finding it to be negligible.

VI. APPLICATIONS AND CONCLUSIONS

The physical sources of the excesses observed in the electron and positron CR fluxes are naturally divided in two classes: charge symmetric and charge asymmetric. The first class is characterized by $r_U = 1$. All other sources, for which $r_U(E)$ depends on the energy or is constant but different from unity, belong to the second class.

This classification applies indiscriminately to any source, be it astrophysical or of DM nature. It is not the goal of this paper to enter in the merit of any specific model. Here we merely classify the main models suggested in the literature with respect to their potential to yield a charge asymmetry. Then we suggest how to use our results about charge asymmetry, expressed in fig. 5, for a straightforward test of any production mechanism.

Astrophysical models

The simplest models of pulsars – see *e.g.* [9] and references therein – are charge symmetric, given that the basic assumption is that pulsars inject the same number of electrons and positrons in the interstellar medium. Our parameterization eq. (13) with $N^U_{e^+} = N^U_{e^-}$ (hence $r_U = 1$) describes well the fluxes from a pulsar expected at Earth.

For supernovae [2, 7, 8, 10] the situation is more delicate. There is a primary source of electrons which is responsible for $B_{e^-}(E)$ and, on top of that, an equal number of positron and electron secondaries produced at the source and which might be responsible for the excesses. Here too the production mechanism for the excesses should correspond to $r_U = 1$.

DM models

Symmetric DM can lead to CRs by either annihilation, decay or both. However, as proven in [11], all models of symmetric DM imply $r_U = 1$ for any energy. A recent re-analysis has been performed in ref. [24].

In order to achieve an $r_U \neq 1$, DM must be asymmetric (therefore decaying) [27, 28] and furthermore violate lepton flavor symmetry [11, 29]. These models lead to an energy dependent r_U. For instance, for an asymmetric DM candidate decaying into $\mu^-\tau^+$ we obtain a naturally increasing behavior for $r_U(E)$, from about 1.5 at $E = 30$ GeV up to a value of 3 at $E = 300$ GeV, see fig. 3 of [11].

For the DM interpretation of the excesses, however, attention must be paid to gamma-ray constraints, see for instance [30].

We have shown that by combining the recent data from AMS-02 with those from Fermi-LAT, a charge asymmetry in the unknown excesses of electron and positron CRs is emerging, favoring the electron component. The result relies on having chosen a conservative estimate for the astrophysical background fluxes. Charge symmetry can be rescued

when adopting an electron background spectral index slightly smaller than the commonly assumed values.

Given that both astrophysical and DM models can be classified according to their predictions for the asymmetry, the impact of the future AMS-02 [4] results for the charge asymmetry will play a crucial role in discriminating the proposed production mechanisms.

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